Calculation of the Optical Constants Using X-ray Reflectometer for Verifying the Optical Design of the Attenuated Phase Shift Mask

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Abstract & Introduction

Extreme ultraviolet lithography (EUVL) is most promising patterning technology to be adopted for 1X nm half pitch (hp). Phase shift mask (PSM) is one of resolution enhancement technology (RET) that makes smaller feature patterning possible and has still been studied to apply this technology to EUVL.
We proposed attenuated PSM structure that consists of 16.5nm TaN absorber layer and 24nm Mo phase shifter layer on 2nm Ru capped 40 pairs of Mo/Si multilayer. This PSM was designed to satisfy 12% EUV reflectivity at pattern stack and 180 degrees phase difference of light reflected from pattern stack and multilayer mirror. To design the optical performance of PSM, we used optical constants obtained from the index of refraction database in CXRO. The optical constants depend on the density of materials and the properties of thin film materials including density are different from bulk materials. If the PSM is manufactured, its optical properties should be different from that of designed one because most of optical constants in CXRO refraction index database are calculated value using density of bulk materials. So we performed this study to verify reflectivity and phase different of manufactured PSM and to modify the design of PSM when it is needed. We deposited TaN and Mo, the phase shifting absorber stack materials, on Si substrates and measured their density with the x-ray reflectometer and calculated the optical constants of the mask stack materials by substituting this density into the equation of complex optical constants at EUV region. The results were compared with database in CXRO and were used for reflectivity and phase different simulation to confirm optical design change of the PSM. To verify the design, we fabricated the PSM blank and measured the reflectivity directly by using EUV reflectometer. As a result, the measured reflectivity was similar to designed value and we confirmed that fabricated PSM had improved optical performance as designed. The simulation of reflectivity and phase difference were performed using the EM-suite provided by Panoramic Technology Inc. and incident angle was 6 degrees. We obtained atomic scattering factor from the database in CXRO.

Equation for optical constants calculation

Equation of Complex refractive index

$$N(\omega) = n(\omega) + i\beta(\omega)$$
$$= 1 - \delta(\omega) + i\beta(\omega)$$
$$= 1 - \frac{r_0 \lambda^2 N_A}{2\pi} \sum \frac{\rho_j}{m_j} \left[f_{1j}(\omega) - i f_{2j}(\omega) \right]$$

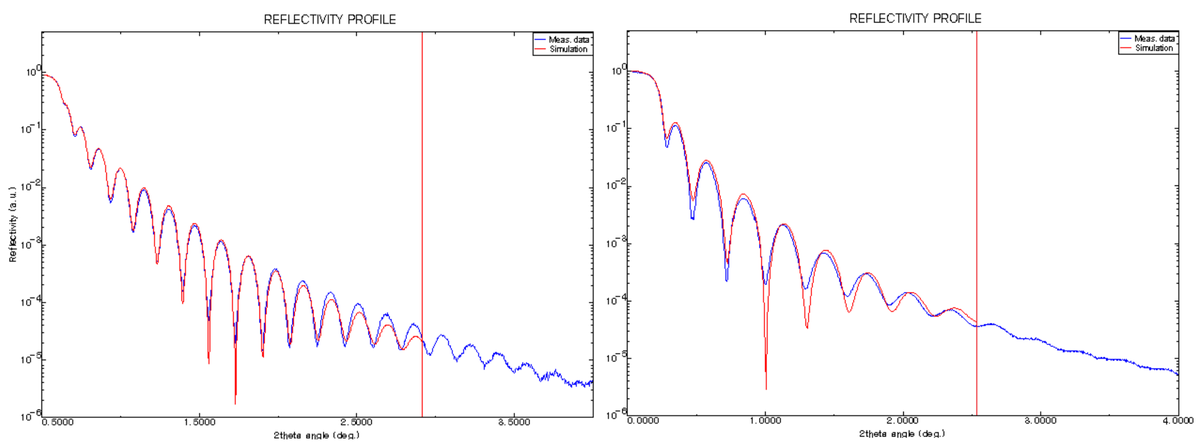
r_0 : classical electron radius N_A : number of Avogadro
ρ : density of material m : atomic mass
f : atomic scattering factor ω : frequency

✓ Density can be measured by x-ray reflectometer, atomic mass and atomic scattering factor can be obtained from database of website 'Chemecal Elements' and 'the Center for X-Ray Optics', and the other terms are constant values

Equation terms	TaN	Mo
Wavelength (λ)	13.5 nm = 1.35 × 10^{-8} [m]	
Electron radius (r_0)	2.81794 × 10^{-15} [m]	
Avogadro's number (N_A)	6.02214 × 10^{23} [atom/mol]	
Atomic mass (m)	194.95 [g/mol]	95.94 [g/mol]
Real part of atomic scattering factor (f_1)	12.9633	14.4185
Image part of atomic scattering factor (f_2)	10.5924	1.19436
Film density (ρ)	**XRR measurement**	**XRR measurement**

Results & Discussion

XRR measurement data & fitting using simulation



X-Ray Reflectivity of TaN thin film *X-Ray Reflectivity of Mo thin film*

✓ From the results of this measurement, we get the density of TaN and Mo thin film layer. The density of TaN thin film layer is 12.54483 g/cm^3 and the density of Mo thin film layer is 9.35676 g/cm^3

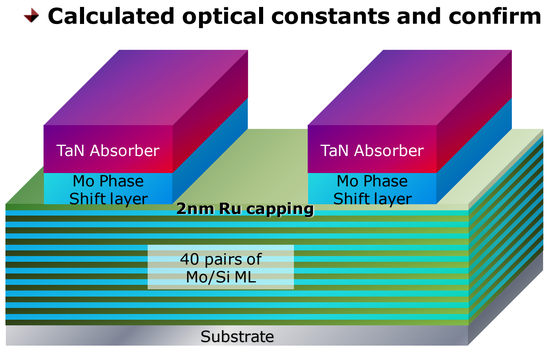
Results & Discussion

Density, Stoichiometry and Atomic fraction from XRR and XPS measurement

Materials	Elements	Stoichiometry	Atomic fraction	Density (g/cm^3)
TaN	Ta	4.0	0.97467	12.22713
	N	1.0	0.00646	0.08108
	O	0.3	0.1886	0.23662
	Total			12.54483
Mo	Mo	1.0	0.96772	9.05476
	O	0.2	0.03228	0.30200
	Total			9.35676

Results & Discussion

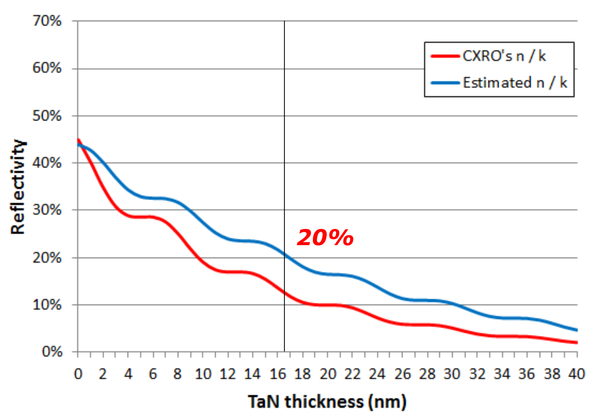
Calculated optical constants and confirm the mask design



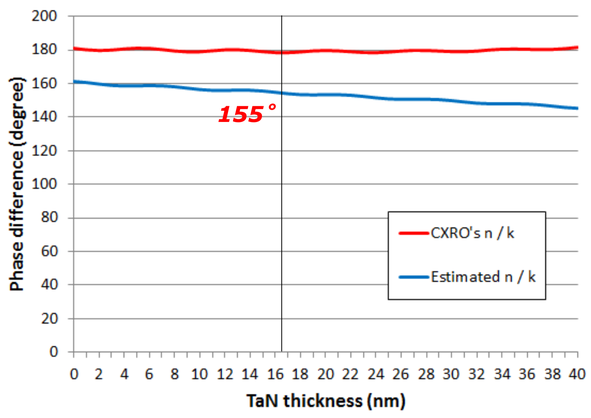
Materials	Density (g/cm^3)	n	k
TaN	12.54483	0.95212	0.03197
Mo	9.35676	0.92693	0.00827

Design of phase shift mask (left image) and estimated optical constants of TaN and Mo thin films (right table)

Reflectivity and phase difference of PSM



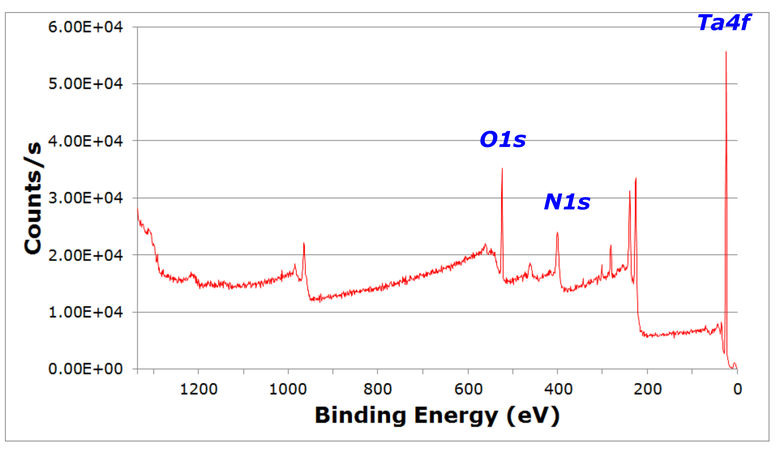
Reflectivity of PSM according to thickness of TaN



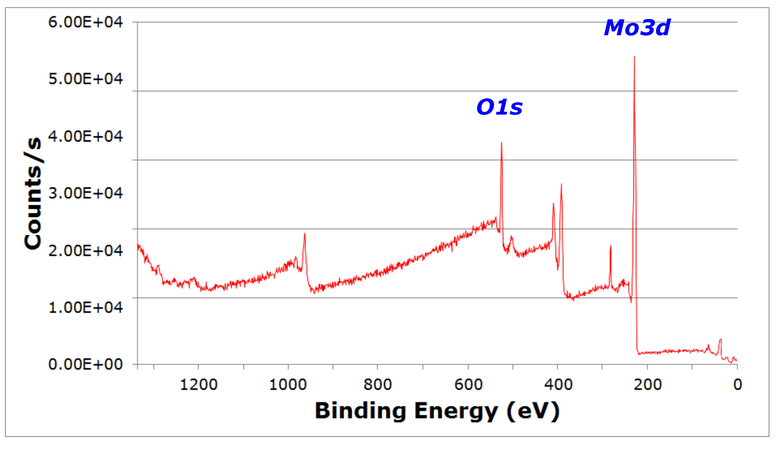
Phase difference of PSM according to thickness of TaN

Results & Discussion

XPS spectrum : Quantification regions



Quantification regions of XPS spectrum of TaN thin film

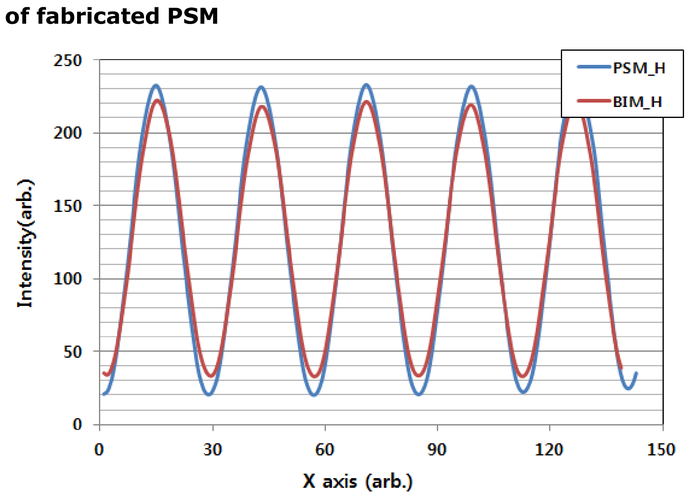


Quantification regions of XPS spectrum of TaN thin film

✓ Atomic fraction and stoichiometry can be obtained from this XPS measurement and the values are tabled left side

Results & Discussion

Intensity profile of fabricated PSM



✓ We fabrecated the PSM according design of 16.5nm TaN absorber layer and 24nm Mo phase shifter layer on 2nm Ru capped 40 pairs of Mo/Si multilayer and estimated intensity of this PSM using the EUV source included coherent scattering microscopy (CSM) that our laboratory retains

✓ The intensity profile shows that the image contrast of the PSM is increased because increase in the maximum intensity and decrease in the minimum intensity

Conclusion

✓ We prove that our design of the PSM can serve as resolution enhancement for patterning and even though there is a little change of optical constants, the function of the PSM don't decrease greatly

✓ It is necessary that accurate measurement method of the optical constants because the density of thin film materials is quite lower than bulky materials and this makes that design of reticle need to be modified

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